# Orbital Dynamics Considerations for Low Perigee Satellite Missions in the Earth's Lower Ionosphere

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# Orbit Dynamics Considerations

# Primary Orbital Perturbations

- **The major perturbations affecting these satellites are the atmospheric drag and the Earth's geopotential, in particular, $J_2$ (Earth's oblatness)**
  - **Atmospheric drag due to the low perigee (in both the parking and dipping orbits) creates an acceleration on the spacecraft which tends to decrease its orbital energy, and thus, the orbit 'decays'**
  - **The perturbation due to the Earth's $J_2$ term has the tendency to precess both the Line of Apsides (the line connecting perigee and apogee) and the Line of Nodes (the line connecting the ascending and descending nodes)**

- Orbital drag acceleration is defined as

$$a_{Drag} = \frac{1}{2}\frac{C_D A}{m}\rho V_{rel}^{2}$$

where:

  - $\rho$ = density
  - $C_D$ = drag coefficient
  - $A$ = drag profile area
  - $m$ = mass
  - $V_{rel}$ = s/c velocity relative to atmosphere

- Currently use the Jacchia-Roberts 71 model for atmospheric density calculations

- Precession of Lines of Apsides ($d\omega/dt$) and Nodes ($d\Omega/dt$)

$$\frac{d\omega}{dt} = \frac{3n J_2 R_E^2 (4 - 5\sin^2 i)}{4a^2(1-e^2)^2}$$

$$\frac{d\Omega}{dt} = \frac{-3n J_2 R_E^2 \cos i}{2a^2(1-e^2)^2}$$

where:

  - $J_2$ = Earth's $J_2$ zonal coefficient
  - $R_E$ = Earth equatorial radius
  - $a$, $e$, $i$ = orbit semi-major axis, eccentricity, and inclination (respectively)
  - $n$ = orbit mean motion $(\mu/a^3)^{1/2}$

# Effects of Orbital Drag

- Differences in the mass/area ratio (m/A) and atmospheric density (due to solar activity) affect the orbital decay during this sample high latitude (> 65°) dipping campaign to 135 km.
- The simulations use m/A values ranging from 250 ⇨ 1000 kg/m$^2$ at times near both solar minimum and maximum.
- The apogee decay rate (km/orbit) increases as m/A decreases (nearly linear);
  - -0.50, -0.75, -1.25, -2.25 km/orbit with density ranging from 5 - 6 kg/km$^3$ (Solar Minimum)
  - -0.75, -1.00, -1.50, -3.00 km/orbit with density ranging from 6.5 - 7 kg/km$^3$ (Solar Maximum)
- Most efficient deep dips are at beginning of life (BOL) when m/A is largest. Efficiency drops at propellant is depleted.
- For comparison, previous study m/A values:
  - LOPEX: 294 ⇨ 183 kg/m$^2$ (BOL ⇨ EOL)
  - DIPPER: 494 ⇨ 140 kg/m$^2$ BOL ⇨ EOL)
  - GEC: 555 ⇨ 334 kg/m BOL ⇨ EOL)

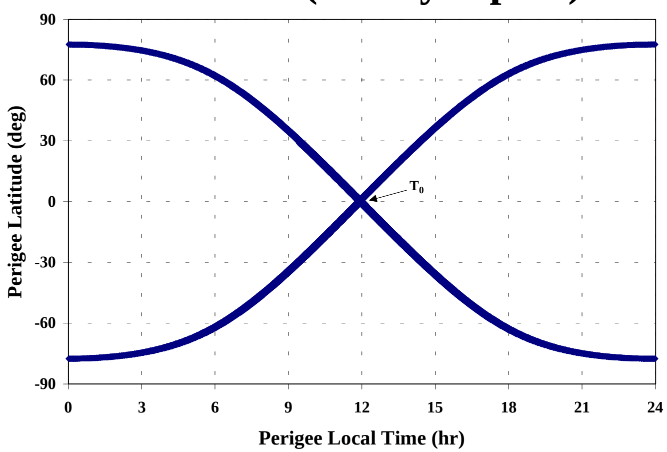
## Result

- Atmospheric drag effects must be countered with frequent maneuvers to restore apogee

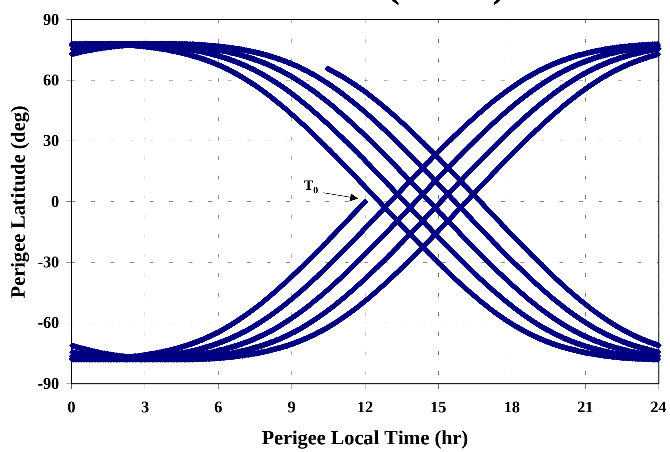
# Perigee Latitude / Local Time Evolution

- **Perturbations on the spacecraft due to $J_2$ will cause the perigee latitude and local time (w.r.t. the Sun) to change over time**
  - **The perigee latitude changes as the orbit argument of perigee ($\omega$) precesses**
  - **The perigee local time changes as the ascending node ($\Omega$) precesses. Furthermore, the local time will 'flip' by 12 hours as perigee passes over the pole**
- **Using the same initial conditions in a 2-year simulation, we see that inclination has a tremendous effect on the evolution of the perigee latitude and local time**
  - ***This feature appears to be unaffected by dipping/parking schemes***
- **Inclination selection can give the scientist some means for obtaining data over a narrow or wide combination of latitude and local time combinations**

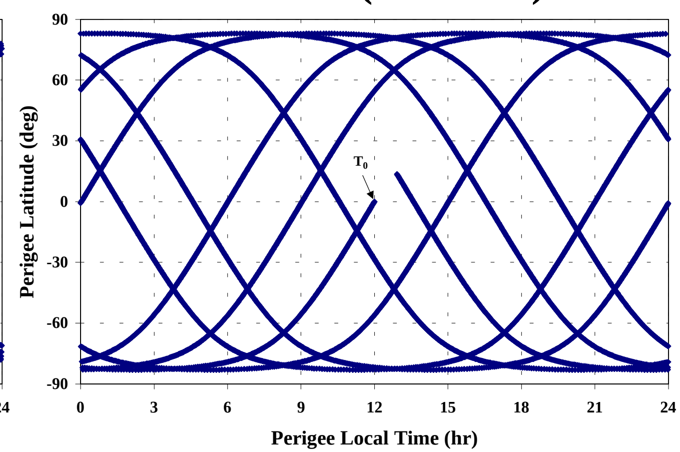
**i = 77.5° (80-day repeat)**




**i = 78.0° (GEC)**

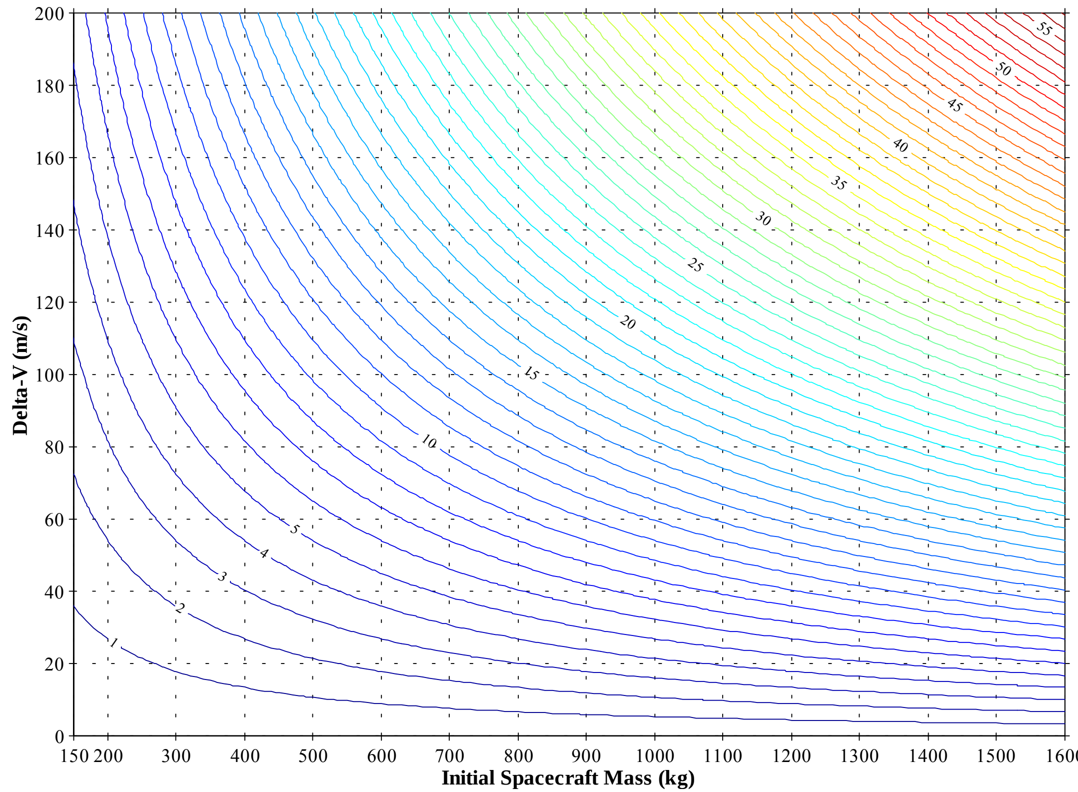



**i = 83.0° (DIPPER)**



# Propulsion Considerations

- **Inherent in the mission design of an ionospheric dipper is the need for a propulsion system to perform orbit maneuvers such as:**
  - **lowering & raising perigee (during dipping campaigns)**
  - **raising apogee (during dipping campaigns)**
  - **formations establishment (GEC)**
- **Typically, there are two choices for propulsion systems**
  - **mono-propellant (Isp = 215 s)**
  - **bi-propellant (Isp = 285 s) - more efficient**
- **Apogee raising maneuvers can be large (60 -115 m/s) so the thrust level must be high enough to minimize the burn duration - don't want to split burn over two successive perigees and lose science data**
- **For GEC formation maintenance, thrust magnitude must allow for precise control of each s/c - challenge for GEC propulsion design**




**Sample thrust contour plot showing thrust duration (minutes) as function of Δv and s/c mass - assumes hydrazine propulsion system and 20 lbf thrust**

# Mission Study Results

# Ionospheric Dipping Missions Previously Studied at NASA/GSFC

- Over the past seven years, the Goddard Space Flight Center (GSFC) has studied several ionospheric dipping missions (see below)
- These missions employ high inclination, elliptical parking orbits (200 x 2000 km) which facilitate periodic dipping campaigns into the lower ionosphere (< 150 km)

## LOPEX - Low Perigee Explorer

- SMEX proposal, 1993
- 1 - 2 year proposed mission
- ≈ 1500 dips below 150 km (max dip to 125 km)
- Dips occur at latitudes > 65° N
- Launch Vehicle: Pegasus-XL
- Spacecraft Characteristics
  - Mass = 250 kg (wet)
  - Frontal Area = 0.85 $m^2$
  - Mprop = 94 kg
  - Propellant: hydrazine
  - $\Delta v$ = 994 m/s

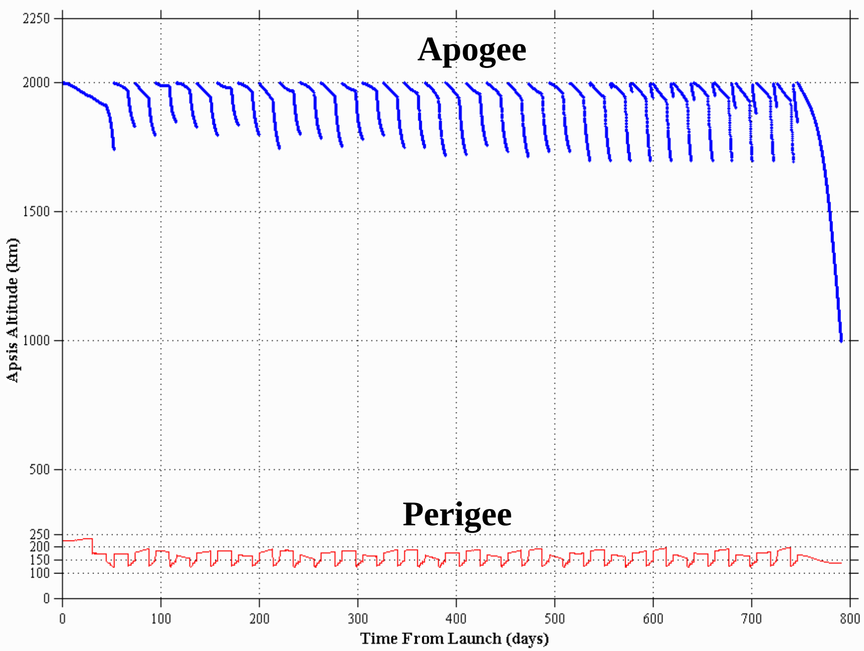
## DIPPER

- MIDEX proposal, 1998
- 2-year proposed mission
- > 3000 dips below 150 km, > 10,000 dips below 200 km, (max dip to 120 km)
- Dipping occurs at all latitudes and local times
- Launch Vehicle: Delta 7320
- Spacecraft Characteristics
  - Mass = 1606 kg (wet)
  - Frontal Area = 3.25 $m^2$
  - Mprop = 1150 kg
  - Propellant: Bi-propellant
  - $\Delta v$ = 3,015 m/s

## GEC - Geospace Electrodynamic Connections

- Study in progress as part of the Sun-Earth Connections program
- Four identical spacecraft executing simultaneous dipping campaigns (max dip to 130 km)
- 2-year mission
- Early study showed potential > 1000 dips below 135 km
- Launch Vehicle: Delta 7920
- Spacecraft Characteristics (each)
  - Mass = 666 kg (wet)
  - Frontal Area = 1.2 $m^2$
  - Mprop = 265 kg
  - Propellant: hydrazine
  - $\Delta v$ = 1,069 m/s

# Sample Ionospheric Dipping Profiles




## DIPPER

- Executed 34, 1-week dipping campaigns at all latitudes and local times to perigee heights between 120 and 150 km followed by a 2-week stay in a parking orbit

## GEC

- Executed 11, 1-week dipping campaigns at all latitudes and local times to perigee heights between 130 and 135 km followed by a 9-week stay in a parking orbit

Apogee

- In each case, apogee maintained above 1500 km (GEC) or 1700 km (DIPPER) for several reasons
  - higher apogees allow for longer ground station contacts for downloading data
  - limiting apogee decay keeps apogee reboost maneuvers small

Perigee

# Simulated DIPPER Results

**DIPPER Perigee History**

**$T_0$ for Dipping Campaigns**

**Perigee Passes vs. Perigee Height**

| Altitude Range | #Dips |
|---|---|
| Hp < 125 | 406 |
| 125 < Hp < 130 | 692 |
| 130 < Hp < 135 | 266 |
| 135 < Hp < 140 | 1083 |
| 140 < Hp < 145 | 596 |
| 145 < Hp < 150 | 448 |
| 150 < Hp < 160 | 436 |
| 160 < Hp < 170 | 1653 |
| 170 < Hp < 180 | 1723 |
| 180 < Hp < 190 | 2309 |
| 190 < Hp < 200 | 530 |
| Total < 150 | 3491 |
| Total < 200 | 10142 |

**Perigee Latitude/Local Time History**

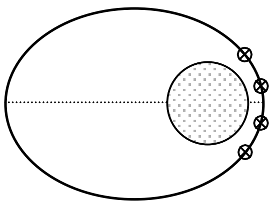
- Red - Dipping
- Black - Parking

# GEC Multiple Satellite Concepts

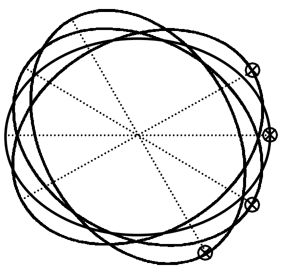
# Multiple Satellite Concepts

- The GEC mission plans to fly four spacecraft in formation, with all s/c periodically dipping to 130 km during planned campaigns

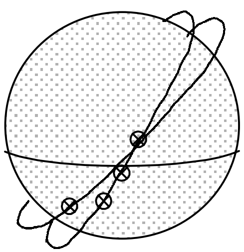
- Several formations have been discussed for GEC
  - ‘String of Pearls’ - s/c fly in formation in same orbit at varying distances



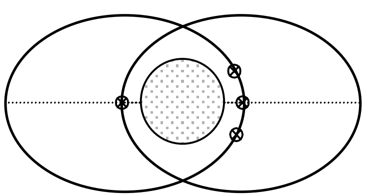
  - ‘Petal’ - s/c perigees are staggered in latitude. Individual s/c are phased in their orbits to obtain altitude profiles.



  - Local Time separations - one s/c orbit is staggered in local time relative to the other three s/c



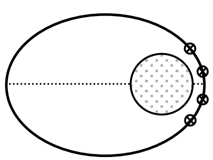
  - Perigee Flip - one s/c orbit is flipped relative to the other three s/c

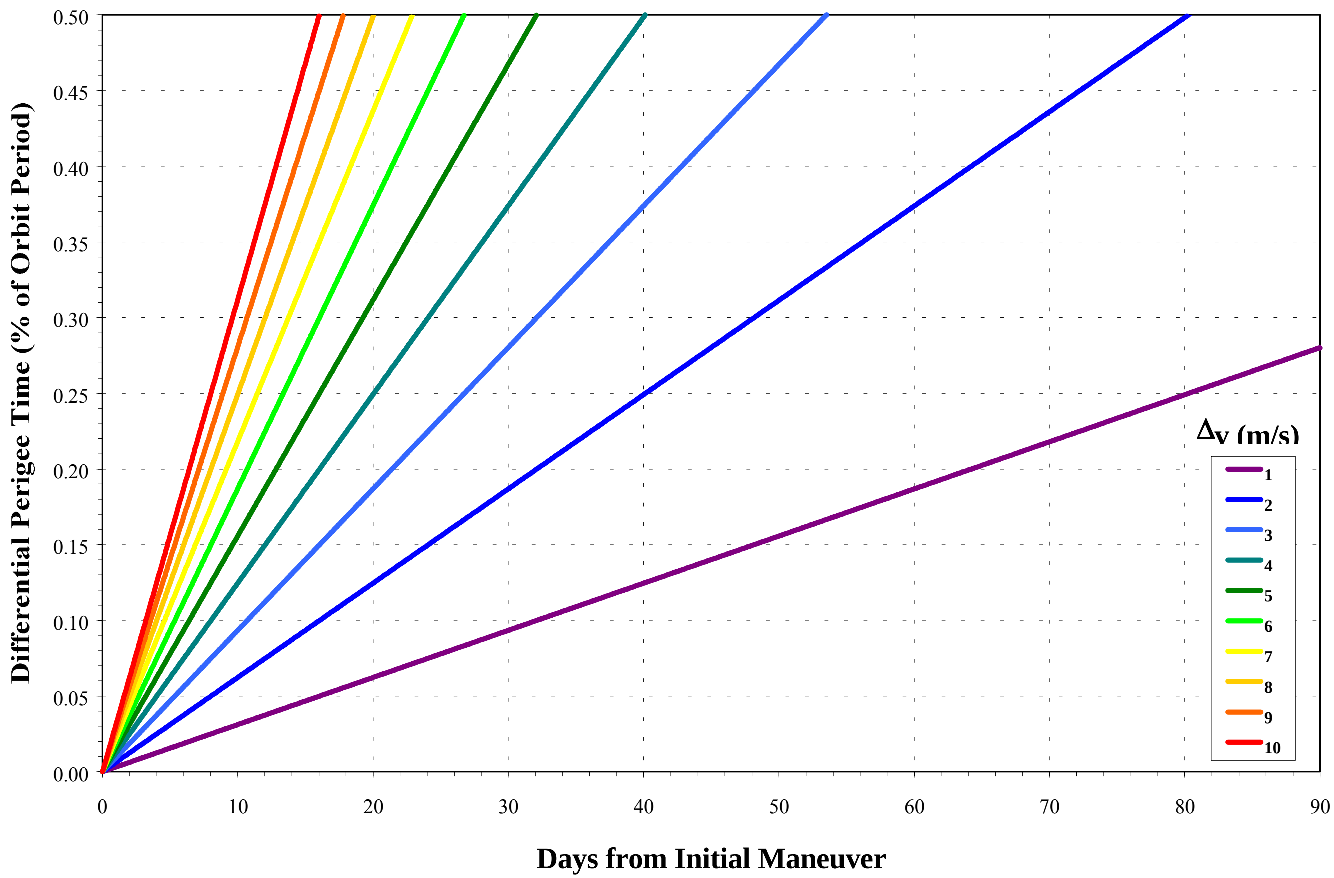


- All of these configurations require maneuvers to establish (and maintain) the formation - in addition to the performing the dipping campaigns

# 'String of Pearls'

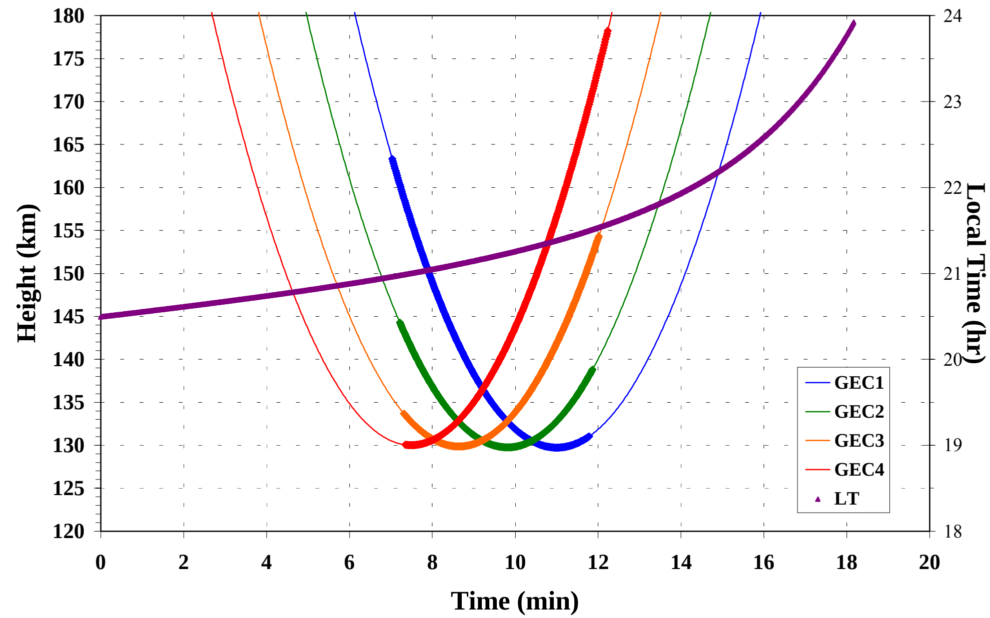
- In the 'String of Pearls' concept, the s/c-to-s/c separation along the orbit (i.e. true anomaly) may vary from 1 second to a quarter-orbit
- This can be achieved with a maneuver to create relative drift between two s/c followed by a second maneuver to stop the drift.
- The plot below shows how quickly the relative distance between two s/c can be achieved (in terms of % of orbit) as a function of Δv expenditure
- The amount of Δv required to perform the maneuvers is inversely proportional to the amount of time needed to achieve the relative drift
- Maintenance may be required over time, depending on the spacing tolerance

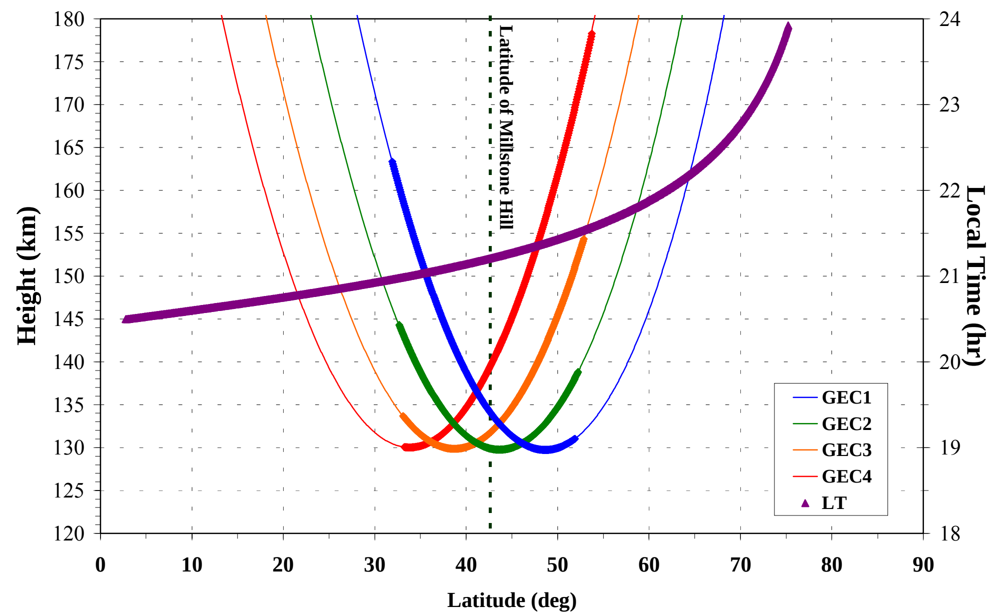




# Orbit 'Petals'

- The orbit petal concept could allow the 4 GEC s/c to obtain different altitude baselines as they pass through perigee
- This example has the perigee latitude of each s/c separated by 5° at a cost of 23 - 65 m/s (based on 200 x 2000 km parking orbit) - this corresponds to ≈ 6% of the available GEC propellant
- An optimal dipping campaign (to 130 km) was simulated to occur over the Millstone Hill radar (for coincident ground observations - highlighted portion of plot)
- The top plot shows the altitude histories of the four s/c as a function of time while the bottom plot shows altitude vs. latitude. The purple line shows the local time variation.
- In this configuration, altitude profiles may be obtained with baselines ranging from 5 - 50 km over the perigee pass
- Further work will be necessary to see how quickly this configuration diverges

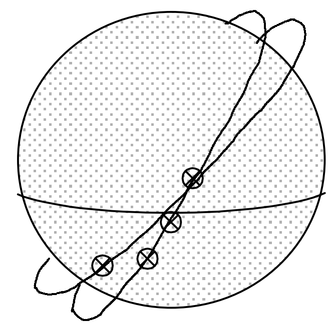


# Local Time Separation

- **Changing the orbit plane of one of the s/c relative to remaining three could allow for perigee passes at different local times**
- **The cheapest way to achieve this is through relative nodal phasing - where one orbit is perturbed relative to a baseline to establish nodal drift over time.**
- **Again, the cost is inversely proportional to the length of time needed to achieve the separation.**
- **A $\Delta$v cost was computed to accomplish a local time drift of 15, 30, or 60 minutes in a duration of 3 or 6 months (assuming the GEC parking orbit (200 x 2000 km)**

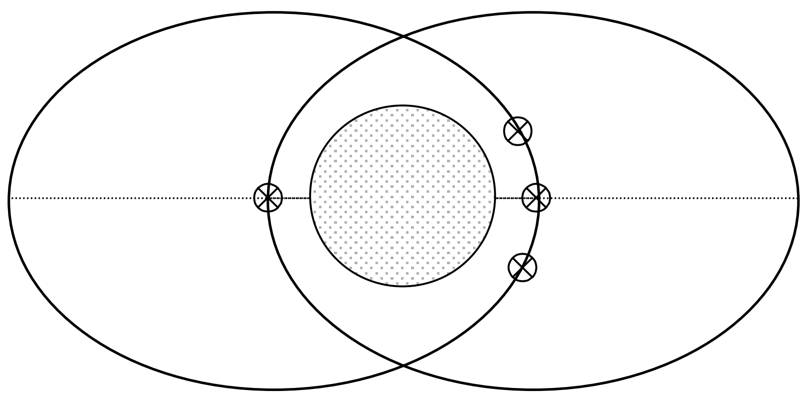
| | **$\Delta$MLT (min)** | | |
|---|---|---|---|
| **Months** | **15** | **30** | **60** |
| 3 | 12.0% | 23.5% | 45.2% |
| 6 | 8.7% | 17.2% | 33.1% |



- **Even a small nodal drift requires a significant amount of propellant**
- **Furthermore, with the perigee latitude is precessing twice as fast as nodal rate - the desire to pass through perigee at different local times is lost**

# Perigee Flip

- Another concept examined involved flipping the perigee of one s/c orbit relative to the other three
- In this configuration, dipping campaigns could sample the ionosphere simultaneously at local times 12 hours apart
- Unfortunately, the $\Delta v$ required to establish this configuration was prohibitive - it required over 75% of the GEC baselined propellant
- Using so much propellant would severely limit the number of simultaneous dipping campaigns



# Conclusions

- Several Ionospheric dipping missions have been studied at NASA/GSFC
- Deep ionospheric missions are challenging and benefit greatly from a capable propulsion system (large propellant mass fraction) and a small cross-sectional area
- The choice of the orbit inclination can greatly affect the variety of perigee passes through different latitudes and local times over the course of the mission
- Making the leap from a single s/c to multiple spacecraft further complicates the problem
  - Propellant must be allocated to transition between potential configurations
  - Operating four maneuvering s/c simultaneously will be a challenging proposition
  - Further work will include the examining the implications of mass differences between each GEC s/c